'DSTAR' -- DIRECT SEA-T^-AIR REFUELING
(INFLIGHT REFUELING OF MILITARY CARGO AIRCRAFT
FROM SHIPS AT SEA)

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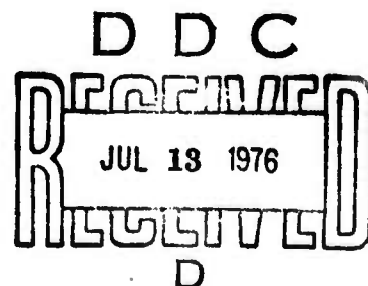
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"DSTAR" -- Direct Sea-To-Air Refueling

(Inflight Refueling of Military Cargo Aircraft
From Ships at Sea)

By: RICHARD L. GARWIN

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Preliminary analysis shows that military cargo and combat aircraft can refuel in five minutes directly from a tanker in the ocean (or a depot on land) by flying in a tight circle while connected to a refueling mast by means of a hose through which fuel is pumped. The aircraft need not carry a hose, cable, or winch. A bank angle of 45°, a circle of radius 400 m, pump pressure of 1500 psi, and aircraft altitude of 120 m allow DSTAR of aircraft from 25 to 350 tons gross. For a C-5A at 350 tons weight, the hose tension is 20 tons; for a 25-ton fighter a lighter hose is used. For the smaller aircraft the hose should be faired to reduce drag.

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PRICES SUBJECT TO CHANGE

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LIST OF ILLUSTRATIONS

I INTRODUCTION

Even under normal commercial circumstances, consideration of range-payload tradeoffs, vehicle productivity, and general utilization of capital might drive one toward the use of ordinary sea-borne tankers for refueling fully loaded cargo (or even passenger) aircraft. Thus, while the C-5A full payload is 220,000 lbs with a range of 3000 miles, at 5500-mile range its payload capacity is reduced to 100,000 lbs.

For supply of U.S. military and allies, it is even more important to refuel enroute. During the "October War" of 1973, USAF military airlift command ("MAC") aircraft did not land and refuel at NATO bases while carrying material from the United States to Israel. As is well known, we did use the Azores, without which our effort would have been severely impeded.

Even if allied bases were freely available to the United States, the U.S. negotiating position for continuing access to these bases might be much improved if there were a practical alternative to continuing use of the bases.

All in all, I would characterize the need for at-sea in-flight refueling capability as something between urgent and critical.

II AT-SEA IN-FLIGHT REFUELING ALTERNATIVES

Several alternatives were briefly considered before fixing upon the concept analyzed here:

(1) Floating islands to replace land bases.

(2) Floating (anchored) airfields.[1]*

(3) Modifying cargo aircraft to allow landing on more-or-less normal aircraft carriers.

(4) Development of a very-short-range, very large tanker aircraft that could fly from an aircraft carrier to refuel large cargo aircraft passing overhead.

These were all rejected in contrast to the instant concept because of their high capital costs, inflexibility, vulnerability, etc.

III CONCEPT

In-flight at-sea refueling as described here requires an aircraft to fly in a tight pylon turn centered on a normal tanker vessel of small-to-intermediate size equipped with a small amount of specialized equipment. The aircraft is minimally modified (no winch, etc.). The idea is for the aircraft to fly in a tight circle at a few hundred meters altitude, attached by a hose of substantial diameter to a short mast on the tanker. As the aircraft flies at a speed safely above stall speed, a pump on the tanker forces fuel through the hose into a refueling inlet on the aircraft. We shall consider a nominal "drink" duration of five minutes.

Rather than a full analysis, this report is a sketch of the required calculation, but I believe it shows the concept to be both attractive and feasible.

Figures 1 and 2 represent the actual refueling phase. Here we see an aircraft of mass M, moving at velocity v in a circle of radius r, at constant height h, about a stationary tanker vessel. It is linked to

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* References are listed at the end of the report.

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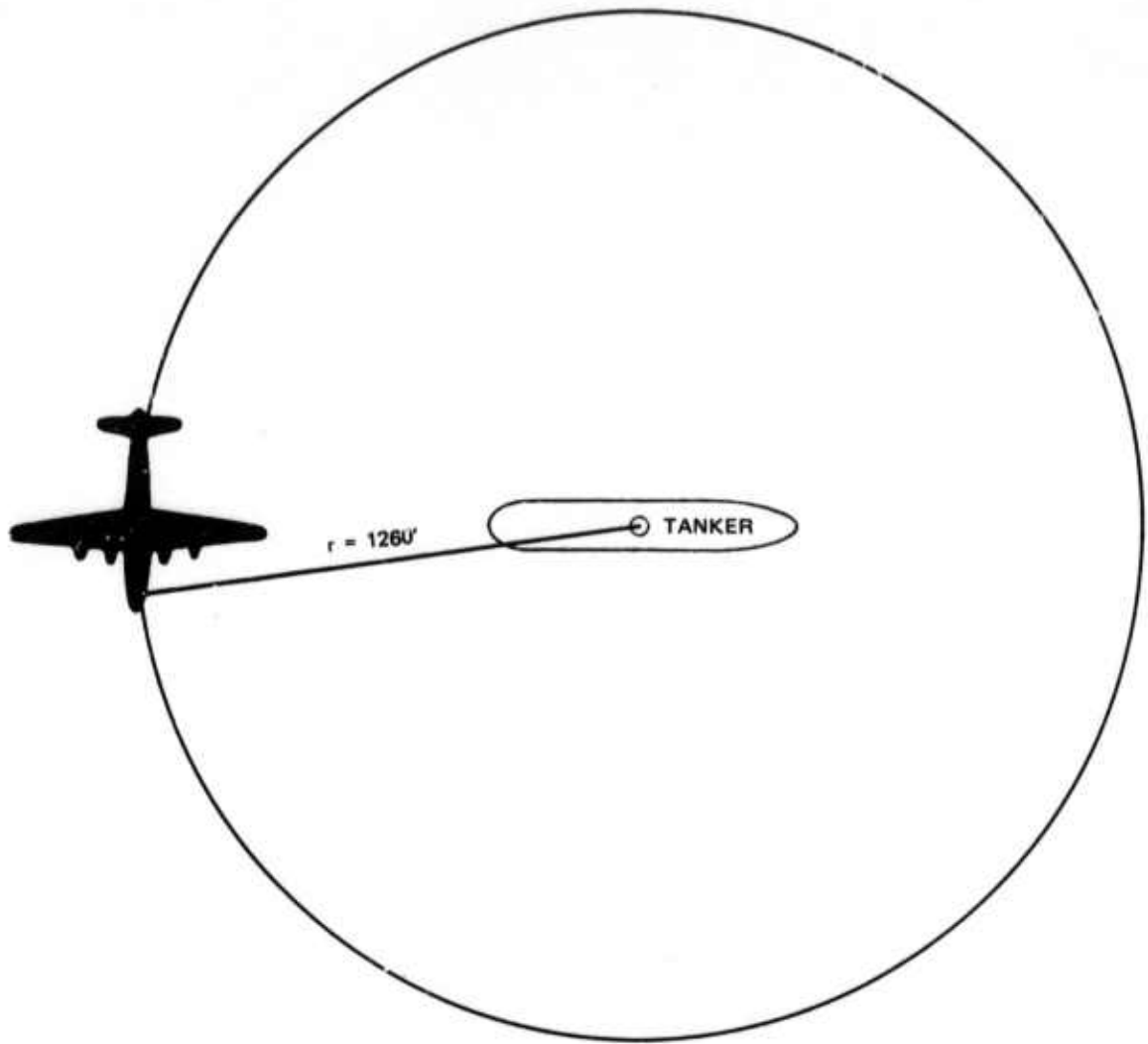
FIGURE 1   A LARGE CARGO AIRCRAFT IS PILOTED TO FLY AT RADIUS r FROM A
TANKER SHIP UNDER WAY AT LOW SPEED. The aircraft is at altitude h.
It drinks a full load of fuel from the hose in 5 minutes. To avoid stability
problems, hose weight and drag are kept below a few percent of aircraft lift,
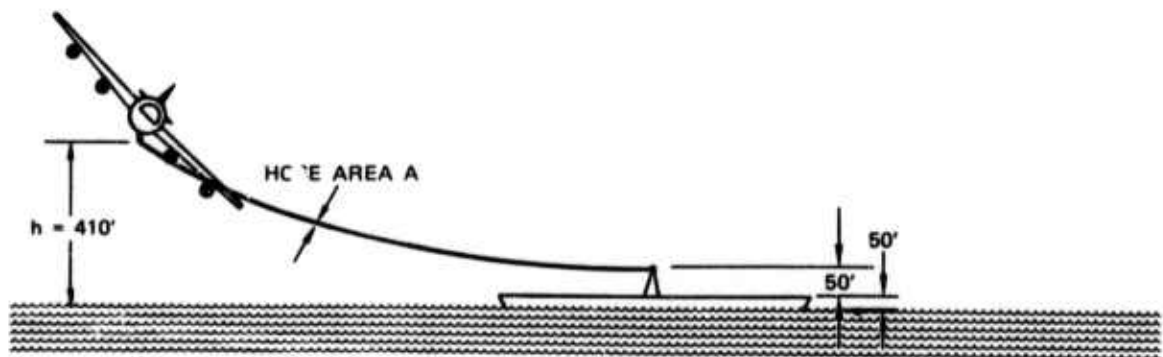centripetal force, or thrust.

FIGURE 2   ELEVATION VIEW OF THE REFUELING OPERATION OF FIGURE 1,
SHOWING AIRCRAFT IN QUASI-FREE FLIGHT, BANKED AT 45°

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that vessel by a hose of cross-sectional area A. There are at least two regimes that will allow an aircraft to maintain this flight pattern--one in which the aircraft flies essentially freely, banked at an angle that will supply the centripetal force to move it in the designated circular path. This is the condition considered here. An alternative is to allow the centripetal force to be provided by the tether to the ship, requiring very much larger tensions in the hose, and presenting greater questions of stability of the aircraft in flight. This regime is by no means excluded, and has some potential advantages, but is not analyzed here.

One would like to make the radius of the circular pattern as small as possible in order to make the weight of the fluid-filled hose small, but the centripetal force required becomes larger with small r. Thus the required bank angle of the aircraft is larger, as is the total lift L which the aircraft must provide in order to fly in the circular pattern. We do not optimize the radius here, but take a reasonable radius--that for which the aircraft bank angle is 45°, so that the aircraft lift is 1-g vertically, 1-g centripetally, for an overall lift L, which is given by

$$\vec{L} = Mg \; \hat{z} - Mv^2 r^{-1} \; \hat{r} \tag{1}$$

and

$$|L| = Mg[1 + (v^2/gr)^2]^{1/2} \tag{2}$$

and for the special case is

$$|L| = Mg \cdot 2^{1/2}$$

Here we have assumed the hose and its contained fuel to be weightless and without drag. We shall return to these assumptions later.

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If the safe landing speed of the aircraft is v_L, with say, 20% margin over stall speed, then a lift of 1.41 Mg can be provided at a fueling speed

$$v_F^2 = v_L^2 \ (L/Mg) = v_L^2 \ 2^{1/2} \tag{3}$$

or

$$v_F = v_L \ 2^{1/4} \quad . \tag{4}$$

Thus, with

$$v_F^2 = gr \quad ,$$

(a 45° bank angle, and a total load factor on the aircraft of 1.4 g), we find for the radius of the circle

$$r = 2^{1/2} \ v_L^2/g \tag{5}$$

and for

$$v_L = 100 \text{ knots} = 169 \text{ ft/s} = 51.5 \text{ m/s} \tag{6}$$

we have

$$r = 1262 \text{ ft} = 385 \text{ m} \quad .$$

A. Pump Power and Pressure

Assume that we want a drink duration of 5 minutes or 300 s, and that the aircraft needs to take on 100 tons of fuel. This is then a drink

rate of about 330 kg/s, or a fuel flow rate of D = 500 liter/s. The hose area is A cm^2. What is the required pump pressure? Assume for the moment that the kinetic energy of the fluid at velocity v_f in the hose is lost in a distance

$$d_A = kA^{1/2} \quad , \quad \text{with } k \sim 50.$$

The required pump pressure is

$$P = [1/2 \, \rho \, (v_f)^2] \; r/d_A \tag{7}$$

$$P = 1/2 \, \rho D^2 rk^{-1} A^{-5/2} \tag{8}$$

with $\rho = 0.7$ g/cm^2, D = 5×10^5 $cm^3 s^{-1}$, r = 3.85×10^4 cm. We can calculate the mass of the fluid in the hose:

$$M_f = \rho Ar = \rho r (1/2 \, \rho D^2 rk^{-1} P^{-1})^{0.4} \tag{9}$$

$$M_f = (1/2 \, \rho^{7/2} D^2 r^{7/2} k^{-1} P^{-1})^{0.4} \quad . \tag{10}$$

If we want M_f = 10 tons = 10^7 g, we can determine P from Eq. (10) as

$$P = 1/2 \, \rho^{7/2} D^2 r^{7/2} k^{-1} M_f^{-5/2} \tag{11}$$

or

$$P_o = 2.54 \times 10^7 \text{ dyne/}cm^2 = 373 \text{ psi} \quad .$$

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The corresponding hose cross-sectional area is $A_o = 262$ cm^2, with an internal diameter of 18.3 cm (7.2 inches). This very moderate pressure can be increased to 1500 psi or thereabouts, reducing the hose weight to 5.7 tons, or shortening the drink time. Assuming henceforth a 1500-psi supply, one may calculate two additional pressure-related quantities. First there is an additional pressure head $P_c = 1/2 \rho v_F^2$ from the hose's action as a centrifugal pump. This $P_c = 1.312 \times 10^7$ dyne/cm$^2 = 192$ psi.

Second, one might ask what constraints such pressures imply concerning the height h of the aircraft orbit:

$$\Delta P_h = \rho g h \quad .$$

This equation sets a scale, a $\Delta P_h = 200$ psi corresponding to an h = 198 m.

B. How High Must the Aircraft Fly?

For our purposes, we assume a hose tension T large compared with the hose weight--namely, twice. With this approximation, the hose shape is a parabola. We may adjust the aircraft altitude to have the hose leave the mast horizontally and thus avoid dragging in the water. With a hose weight mg and tension T, the aircraft altitude above the mast tip is

$$h = \frac{mg}{T} r/2 = 96 \text{ m} \tag{13}$$

and the hose approaches the aircraft at an angle to the horizontal

$$\theta = mg/T = 0.5 \text{ radians} = 29 \text{ degrees} \quad ,$$

with vertical component of tension about 10 tons and horizontal component

of tension 17 tons, both small compared with the 350-ton components of vertical and horizontal aircraft lift. The aircraft stability should thus be little affected by the hose.

C. How Does this System Scale with Aircraft Size?

We can scale down aircraft weight, fuel load, and hose weight, by a factor s ("smallness"), with the same drink time, accelerations, etc. We have then

$$L = sL_0 \quad ; \quad \rho = \rho_0 \quad ; \quad k = k_0 \quad ; \quad D = sD_0 \quad ; \quad m_f = sm_{f0} \quad .$$

Then we may obtain from Eqs. (11) and (8),

$$P = P_0 S^{-1/2} \quad ; \quad A = A_0 S \quad . \tag{14}$$

For a 50,000-lb fighter versus a 700,000-lb C-5A, S = 0.0714. A five-minute drink duration would thus require a pump pressure for the fighter of

$$P = 373 \text{ psi } S^{-0.5} = 1400 \text{ psi} \quad .$$

The hose tension T is 1.43 tons; the hose area is 37.4 cm^2, with an inside diameter of 4.9 cm or 1.93 inches.

D. Acquisition Maneuvers

Two very distinct maneuvers for acquiring hose will be described here. The first has many applications to naval problems other than simply the refueling of aircraft, and that is the purpose for the description. It was analyzed long ago by John M. Richardson.

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Imagine an aircraft arriving in the neighborhood of the refueling vessel, at an altitude substantially above that which will be used for refueling--say, 1000 meters. Let the aircraft travel in a tight circle of radius equal to that which will be used for refueling, and let it unwind a light line which will initially trail behind the aircraft as the aircraft flies around the circle. If the line has a length substantially greater than the circle diameter, particularly if the end of the line has a small parachute attached to it, the line, instead of following the aircraft around the circle will gravitate to the center of the circle. Further paying out of line will then result in a standing vertical section of line along the axis of the circle, with the top region of the line following the aircraft around the circle. At this point, if the line is further paid out or if the aircraft reduces its altitude, the parachute will approach vertically to the refueling mast. An attendant on the ship (or an automatic mechanism) can then attach a leader to the aircraft line; line and leader can then be pulled into the aircraft and the hose pulled in. The entry of the hose into the refueling socket should be made automatic, so that no local attendant is required. This maneuver may also be useful for strictly naval purposes, such as the emplacement and re-covery of large sonobuoys or oceanographic devices by fixed-wing aircraft. Naturally the Navy could refuel its fixed-wing P-3 aircraft in this way, and the requirement for the Navy continually to practice such an operation in peacetime would provide the opportunity for the use of Naval aircraft in support of oceanographic work, without the extra commitment of resources often required to emplace, tend, and remove oceanographic equipment. This acquisition maneuver requires a winch on the aircraft capable of hauling the line.

The second maneuver, somewhat more straightforward for this specialized need of refueling aircraft, involves the aircraft flying directly over the ship. The aircraft would fly over the short refueling

mast on the ship, would snag the loop of a line stretched between two light masts on the ship, and would set up its refueling orbit. The ship would pay out line to the aircraft, perhaps initially a length greater than eventually required for the radius of the refueling orbit. After the aircraft is stabilized in the refueling orbit the refueling hose would be pushed out from the ship along the leader line, and would insert itself automatically in the refueling socket on the aircraft. In this way, the aircraft need have no long line onboard and no winches. The refueling hose is attached to the leader line by hooks every few feet, and it has ample rigidity initially to be pushed out along the line. After a few hundred feet of hose are deployed, the centrifugal force will take care of the further deployment, the storage drum on the ship serving as a brake.

In either of these cases, at the end of the refueling operation, the aircraft can allow the hose to be pulled back aboard the ship or it could drop the hose in the water to be sucked back aboard the tanker. The second system could be used over land (without possibility of snagging the dropped cable on brush, etc.) if the aircraft were to fly directly over the mast following the refueling operation, allowing the line to be played in under constant tension rather than dropped for later recovery.

During the refueling operation, it is unreasonable to expect that the aircraft will be able to maintain with perfect accuracy the 1260-ft standoff from the ship, and in addition the ship may be rolling in the water. Thus, the ship should be equipped with a constant-tension device, whereby as much as 200 ft or so of cable can be paid out and recovered while maintaining the design tension of, say, 20 tons. This play can be provided from the winch that pays out the hose in the first place, or it may be obtained from an auxiliary cable trough in the ship.

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Automatic piloting, perhaps using the hose as a communications and measuring device, can help to make the refueling maneuver more reliable, less of a strain on the pilot, and less costly in training.

There is no requirement for the tanker to be dead in the water while it is refueling aircraft. In fact, normally one would refuel from a tanker while making perhaps 5 knots, an economical speed that still provides steerage and general control of the ship.

To have least influence on the dynamics of the aircraft, one would like the refueling socket to be near the center of mass of the aircraft, but this could cause the wing to interfere with the leader as the wing dipped down to 45° during the acquisition maneuver. It may be necessary to mount the refueling socket somewhat forward of the wing to avoid this problem, or to increase the aircraft altitude so that the hose enters at an angle sufficiently steep to clear the wing.

E.   Air Drag on the Cable

Since aircraft have a lift-to-drag ratio on the order of 10, it is important to calculate the air drag on the hose and to make sure that it is within the capability of the aircraft thrust. In the equation

$$F_d = 1/2 \; \rho_a v^2 C_d B \tag{15}$$

F_d is the air drag on an area B, being dragged through air density ρ_a at velocity v. The shape has a "drag coefficient" C_d. In the present case, the hose is being swept approximately as a rigid body through the air and we are interested in the force required to move the outer end of the hose. Hence we may calculate this drag force on the aircraft by integrating Eq. (15) in an appropriate manner, equating the moments of the drag about the mast to the moment of the aircraft thrust. Thus we obtain

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$$M_d = \int_{R=0}^{R=r} 1/2 \; \rho_a v_F^2 \left(\frac{R}{L}\right)^2 C_d A^{1/2} \; RdR = Fr \tag{16}$$

where the projected area of the hose per unit length is taken as $A^{1/2}$, and drag force on the aircraft is F. With $C_d = 1$ for a cylinder

$$\rho_a = 1.3 \times 10^{-3} \; g/cm^3 \quad ; \quad A^{1/2} = (262)^{1/2} = 16 \; cm$$

we have

$$F = 3.78 \times 10^9 \; dynes = 3.86 \; tons \quad .$$

While a 4-ton drag is not a big burden for a C-5A or C-141 to pull, the drag does not scale down very rapidly for the smaller hoses that would be used for smaller aircraft. In particular, although we have scaled the weight of the hose in Eq. (14) by a factor S, the drag scales by $S^{1/2}$, and becomes a bigger burden relatively on a smaller aircraft.

Drag can be reduced very substantially by reducing C_d from that appropriate to a cylindrical object being drawn broadside through the air, to that appropriate to a streamlined cylinder (e.g., zero-lift aircraft wing). There is considerable Navy experience with such "faired" cable (or in this case, faired hose). In normal Navy use, the faired cable is used to reduce the drag and to reduce the strumming tendency of cables attached to towed sonars. There is no reason why the drag of a hose broadside should not be reduced by a factor of 10 by the addition of a lightweight plastic cover of appropriate shape. Various possibilities present themselves for convenient handling of this streamlining cover. It can achieve its shape by elastic memory, and be squashed flat

when the hose is wound onto its storage drum. Alternatively, the plastic cover can be stripped from the hose and stored flat on a separate drum and be applied to the hose as the hose is paid out from the mast to the aircraft.

IV RECAPITULATION

It appears desirable and feasible on an urgent basis to develop and demonstrate a capability of refueling slightly modified aircraft, of sizes ranging from 50,000-lb fighters to the largest 700,000-lb cargo craft, from tankers underway at sea. The aircraft would fly over the short refueling mast on the tanker, pick up a leader, and stabilize in a refueling orbit. The refueling hose would then crawl up the leader cable and automatically insert itself into the refueling inlet in the aircraft. The aircraft would drink a full load of fuel in 5 minutes. The tension on the hose and the weight of the hose would be kept below 3% of the aircraft weight, and the drag (by the use of a fairing on the hose) would be kept below a few percent of the aircraft thrust. The hose would then be disconnected from the aircraft and rewound aboard ship. The aircraft would then fly directly over the ship to allow the leader to be rewound.

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